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Type IV Radio Bursts and Associated Active Regions in Sunspot Cycle 24

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Abstract
We study the association of solar Type IV radio bursts with the location of active regions on the Sun during Solar Cycle 24. The active regions associated with moving and stationary Type IV bursts are categorized as close to disk center and far from disk center, based on their location on the solar surface (i.e. $\leq 45°$ or $\geq 45°$, respectively). The location of active regions associated with Type IV bursts accompanied with coronal mass ejections (CMEs) are also studied. We found that $\approx 30-40\%$ of the active regions are located far from disk center for all the bursts. However, it is found that most of the active regions associated with stationary Type IV bursts are close to disk center ($\approx 60-70\%$). The active regions associated with moving Type IV bursts are more evenly distributed across the surface, i.e. $\approx 56\%$ and $\approx 44\%$, close to disk center and far from disk center, respectively. The fact that most of the bursts have active regions close to disk center indicates that these bursts can be used to obtain physical properties such as electron density and magnetic fields of the CMEs responsible for geomagnetic storms.

Keywords Corona · Radio bursts · Type IV · Coronal mass ejections · Active regions

1. Introduction

The Sun, being our nearest star, has significant effects on the near-Earth atmosphere, i.e. space weather. The large-scale explosions on the Sun, known as coronal mass ejections (CMEs) (Howard et al., 1985; Yashiro et al., 2004; Cho et al., 2007; Vourlidas et al., 2010; Webb and Howard, 2012) are often seen in white-light coronagraph images taken with space- and ground-based instruments (Fisher et al., 1981; Brueckner et al., 1995; Howard et al., 2008). Solar radio Type II and Type IV bursts are of particular interest for space weather as their study can help to understand the near-Sun development of interplanetary disturbances (Gary et al., 1985; Pohjolainen, Pomoell, and Vainio, 2008).

Type II bursts originate at the shock in front of a CME and are plasma emissions (Smerd, Sheridan, and Stewart, 1975; Mann, Classen, and Aurass, 1995; Aurass, 1997; Gopalswamy et al., 2005; Kumari et al., 2017b,c). Type II radio bursts, their near-Sun signatures, and

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their source regions have been very well studied previously (e.g. Roberts, 1959; Cliver, Webb, and Howard, 1999; Vršnak et al., 2002; Gopalswamy, 2006; Ramesh et al., 2010; Kumari et al., 2017a, 2019). Type IV radio bursts are most frequently associated with CME flux ropes or footpoints of magnetic loops (Riddle, 1970; Ramesh, Kathiravan, and Satya Narayanan, 2004; Vasanth et al., 2019; Salas-Matamoros and Klein, 2020). These bursts can have variable emission mechanisms, unlike Type II bursts, e.g. plasma emission (Gary et al., 1985; Hariharan et al., 2016; Liu et al., 2018; Morosan et al., 2019) or gryosynchrotron emission (Bain et al., 2014; Sasikumar Raja et al., 2014; Carley et al., 2017). Type II and Type IV bursts can be used to estimate the coronal magnetic field (B) associated with various parts of the CME. For example, Gopalswamy et al. (2012) estimated the B field values as $\approx 1.5 - 1.1$ G at $\approx 1.3 - 1.5$ $R_\odot$ using the shock standoff method and splitband Type II bursts, whereas Sasikumar Raja et al. (2014) estimated the B values as $\approx 1.4 - 2.2$ G at $\approx 1.9 - 2.2$ 1.4 $R_\odot$. Several other authors reported similar values at the same height range (see, e.g., Cho et al., 2007; Tun and Vourlidas, 2013; Sasikumar Raja et al., 2014; Kumari et al., 2017c, 2019, and the references therein).

Long-term statistical studies of Type IV bursts and their association with CMEs/active regions (ARs) are less explored in comparison to Type II bursts (Lara et al., 2003; Kahler, Ling, and Gopalswamy, 2019). Robinson (1978) and Gergely (1986) studied a few Type IV bursts and their relation with CMEs. Recently, Kumari, Morosan, and Kilpua (2021) studied the association of these bursts with CMEs in the previous solar cycle (Cycle 24) based on their spectral properties. Morosan et al. (2021) studied the moving bursts in the rising phase of Solar Cycle 24 using radio images. However, due to the lack of radio-imaging instruments, locating the source region of these radio bursts in the corona becomes almost impossible. One way to locate the initial source of any radio burst is to identify its associated active region. Hence, in this work we study the association of active regions with Type IV radio bursts. The location of active regions associated with Type IV bursts is investigated, and their association with CMEs is studied. The article is arranged as follows. In Section 2, the observational data used for the study are described; in Section 3, the data-analysis method is explained; and in Section 4, the results obtained are discussed and we conclude.

2. Observational Data

The event lists available at the Space Weather Prediction Center (SWPC)[1] were extensively used for this study. SWPC provides the list of all the solar and geophysical event reports every day since 1996.[2] The list contains X-ray events, optical flares, radio bursts, and their intensity, type, impact, associated active regions (ARs), etc. Several observatories report the events, and afterwards they are compiled, combined, and updated on the SWPC website. For radio events, the Radio Solar Telescope Network (RSTN) and a couple of other observatories contribute in reporting the bursts. Radio bursts are classified based on their spectral and temporal appearance in the solar dynamic spectra. The information on Type IV bursts from 01 January 2009 to 31 December 2019 was extracted from the entire event list. It contains: the start and end time, start and end frequency, reporting station, and associated AR. Figure 1 shows the dynamic spectra of the Type IV burst on 24 September, 2011 obtained with the Sagamore Hill Solar Radio Observatory. The start time of this burst was $\approx$ 12:50

[1] https://www.swpc.noaa.gov/products/solar-and-geophysical-event-reports.

[2] ftp://ftp.swpc.noaa.gov/pub/warehouse/.

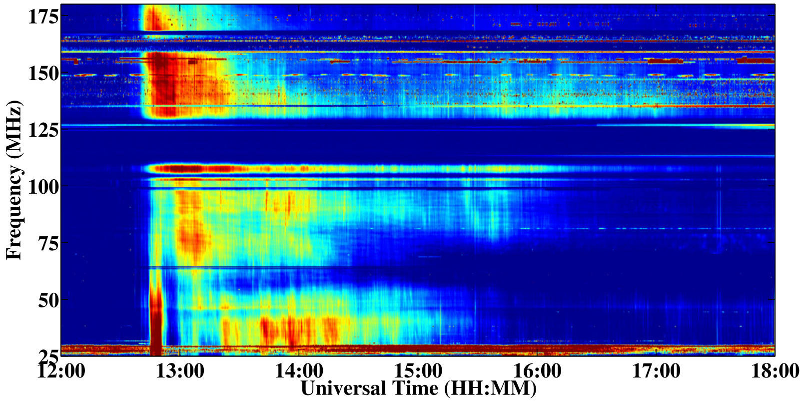


Figure 1 Solar radio dynamic spectra of a Type IV burst recorded at the Sagamore Hill Solar Radio Observatory on 24 September, 2011. This Type IV burst started at ≈ 12:50 UT and lasted till ≈ 17:40 UT. Its frequency range was ≈ 180 – 25 MHz. The horizontal stripes in the dynamic spectra are due to local radio-frequency interference (RFIs).

UT, and it lasted for ≈ 4 hours. The frequency range of this stationary Type IV burst was ≈ 25 – 180 MHz.

For the CME association, we used the list provided at the coordinated data analysis website (CDAW: Yashiro et al., 2004),[3] which contains the manual detection of CMEs with the Large Angle and Spectrometric Coronagraph (LASCO: Brueckner et al., 1995) on board the Solar and Heliospheric Observatory (SOHO). We also used CMEs detected with Cor1 and Cor2 coronagraphs from the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI: Howard et al., 2008) on board the Solar Terrestrial Relations Observatory (STEREO). We used additionally the list provided on the Solar Eruptive Event Detection System (SEEDS)[4] website and the CME list provided by Vourlidas et al. (2017), for which the authors used the dual-viewpoint CME catalog from the SECCHI/COR telescopes.[5]

3. Methodology and Implementation

The SWPC daily event list was used to obtain the active region number and location associated with the Type IV bursts. This list assigns the active region from optical images/GOES Solar X-ray Imager to the radio bursts. Those bursts that had an AR source $\leq 45°$ from disk center were classified as 'close to disk center', and the remaining were classified as 'far from disk center'. The classification of Type IV radio bursts as moving and stationary (Type IVm and Type IVs, respectively) was based on the burst appearance in the dynamic spectra (for details, see Kumari, Morosan, and Kilpua, 2021). We used the drift rate and duration of the Type IV bursts to classify them as Type IVm and Type IVs. A constant drift rate was calculated for both stationary and moving Type IV bursts by using their start and end frequencies, and their duration, $DR = \frac{F_H - F_L}{t}$, where DR, F_H, F_L, and t are the drift rate, start frequency, end frequency, and duration of the bursts, respectively. The bursts with $DR \geq 0.03$ MHz/s

[3] https://cdaw.gsfc.nasa.gov/CME_list/index.html.

[4] http://spaceweather.gmu.edu/seeds/secchi/detection_cor2/monthly/.

[5] http://solar.jhuapl.edu/Data-Products/COR-CME-Catalog.php.

were classified as moving bursts (Robinson, 1978; Gergely, 1986; Kumari, Morosan, and Kilpua, 2021), whereas those with lower drift rates ($DR < 0.03$ MHz/s) were classified as stationary. Robinson (1978) and Gergely (1986) had earlier reported that the moving Type IV bursts have a duration of less than an hour. We used this criteria to further distinguish between stationary and moving Type IV bursts for the bursts that were ambiguous to classify only using DRs. Figure 1 shows the dynamic spectra of a stationary Type IV burst observed on 24 September, 2011.

The CME association of these radio bursts was checked using the CMEs detected with SOHO/LASCO-C2, STEREO-A and -B based on a temporal correlation (for details see Kumari, Morosan, and Kilpua, 2021). The first appearance of a CME in a coronagraph field of view (FOV) depends upon the speed, acceleration, and the propagation direction of the CME with respect to the Sun–Earth line (for LASCO) and the Sun–STEREO line (for STEREO). For the CME–Type IV association, we had two criteria: i) the active region associated with the CME and Type IV should be the same (this was accomplished by comparing the position angle (PA) of the CME with the AR related to the Type IV burst), ii) a CME should appear in LASCO-C2 FOV within ≈ 2 hours of the start time of the Type IV burst (we note that the time between a CME and an associated Type IV can vary depending on the location of the ejection, for example, a limb CME may appear earlier in LASCO-C2 FOV). Both of these criteria had to be fulfilled to assure that the right pair of white-light CME and radio signature were connected. Table 1 contains the number and percentage of Type IV bursts with their AR locations. It also shows the number and percentage of Type IV bursts after classification as moving and stationary. The table lists the Type IV bursts and their association with identified CMEs with SOHO/LASCO and STEREO-A and -B coronagraphs as well.

4. Results and Discussion

Figure 2 shows the location of active regions with which the Type IV radio bursts were associated. Out of the 446 Type IV bursts in Solar Cycle 24, 291 bursts ($\approx 65\%$) had an AR at disk center $\leq 45^\circ$ (see Table 1 for details), hence they were called bursts associated with close to disk center ARs. The rest of them were associated with ARs far from disk center ($\approx 35\%$). Regarding Type IV bursts accompanied with CMEs, almost the same number ($\approx 65\%$) were located close to disk center. Only $\approx 35\%$ of the bursts had ARs far from disk center. Bursts that were not associated with CMEs had flare association (Kumari, Morosan, and Kilpua, 2021). Gopalswamy (2011) suggesting that sometimes the Type IV emission can have a connection to the flare-reconnection site. Type IV emissions can also come from either one or both legs of the magnetic flux ropes, which could also be associated with a failed eruption. Labrum and McLean (1985) summarized that nonthermal electrons related to flares can remain in the corona for several hours, hence we can observe stationary Type IV bursts with any nonidentified CME. We note that between 2014 to 2016, STEREO-A and -B were close to the Sun–Earth line. As faint CMEs traveling close to the observer's line of sight may not be observed in coronagraphs, these coronagraphs as well as LASCO-C2 may have failed to detect CMEs arising from close to disk center. This could increase the number of Type IV bursts without identified CMEs in our list, especially during the above-mentioned period. For moving bursts, the AR locations were almost equally distributed between close to disk center ($\approx 56\%$) and far from it ($\approx 44\%$). Only one Type IVm burst without any identified CME originated far from the disk center in Cycle 24. The AR location distribution of stationary Type IV bursts was almost identical to that of all the Type IV bursts together with $\approx 67\%$ and $\approx 33\%$, close to and far from disk center, respectively.

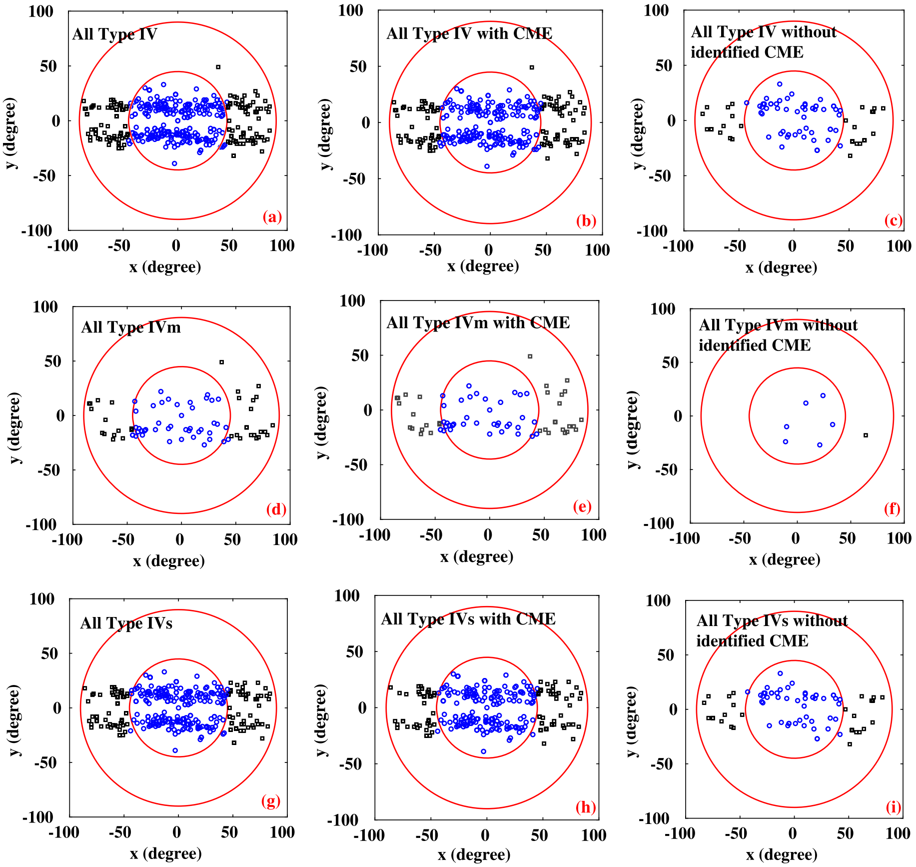


Figure 2 Active region location of: (**a**) all Type IV bursts, (**b**) all Type IV bursts with CMEs, (**c**) all Type IV bursts without identified CMEs, (**d**) all moving Type IV bursts, (**e**) all moving Type IV bursts with identified CMEs, (**f**) all moving Type IV bursts without identified CMEs, (**g**) all stationary Type IV bursts, (**h**) all stationary Type IV bursts with CMEs, (**i**) all stationary Type IV bursts without identified CMEs. The *blue* and *black* points represent close to and far from the disk center locations, respectively. The *inner* and *outer red* circles represent the 45° mark and the solar photosphere, respectively. The axes are marked in coordinates from $-90°$ to 90° from south to north and east to west on the solar surface.

Figure 3 shows the year-wise distribution of the associated active region with the Type IV bursts. This figure also shows the histograms of moving and stationary Type IV bursts both close to and far from the disk center, along with their CME association. We used Gaussian fits for the histograms. For all the Gaussian fits, the peaks lie between 2013 – 2014, which was also the peak for Solar Cycle 24. This indicates that the occurrence of Type IV bursts was directly dependent on the solar-cycle variation. The fits indicate that $\approx 20 - 40\%$ of the bursts occurred during solar maxima. The only moving Type IV burst that had an AR far from the disk center occurred during the declining phase of Cycle 24. We noted that there were more Type IV bursts occurring during the rising period of Solar Cycle 24 than during its declining phase.

There were no Type IVm bursts associated with an AR close to the disk center during the beginning of Cycle 24 (see Figure 3g). In a similar way, no Type IVs bursts originated

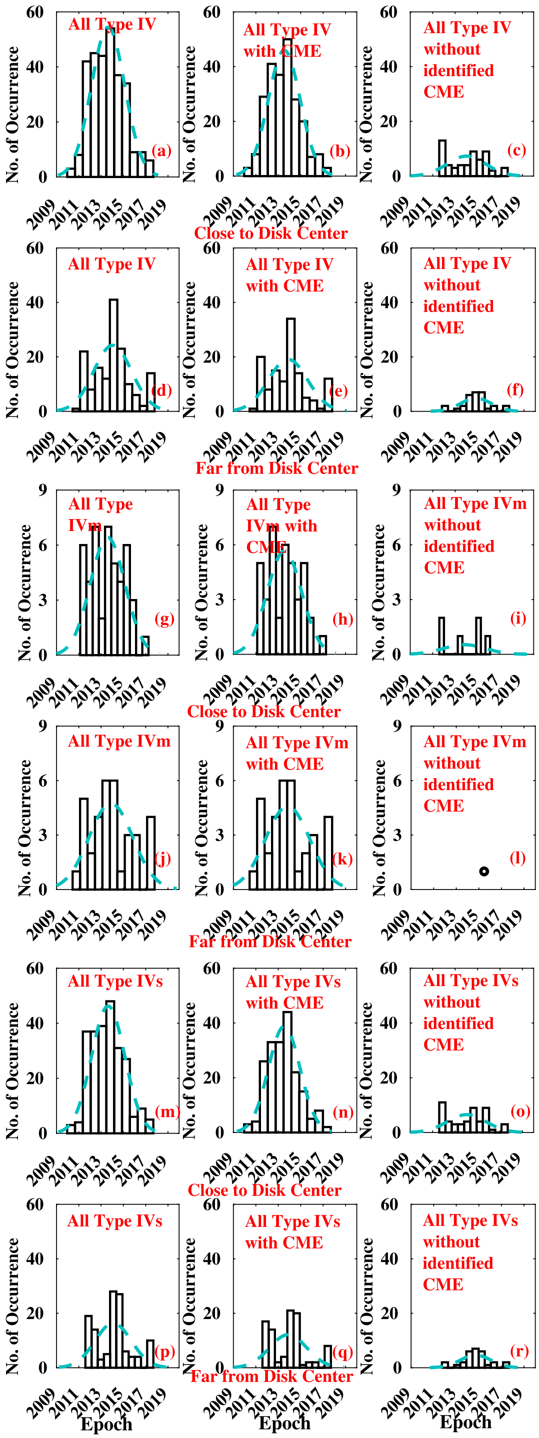
Table 1 Type IV bursts and their associated active regions.

Description	All	Close to disk center	% Close to disk center	Far from disk center	% Far from disk center
Type IV	446	291	65%	155	35%
Type IV with CME	359	234	65%	125	35%
Type IV without identified CME	87	57	66%	30	34%
Type IVm	80	45	56%	35	44%
Type IVm with CME	73	39	53%	34	47%
Type IVm without identified CME	7	6	86%	1	14%
Type IVs	366	246	67%	120	33%
Type IVs with CME	286	195	68%	91	32%
Type IVs without identified CME	80	51	64%	29	36%

from an AR far from disk center either during the same period. Almost all the moving Type IV bursts without any identified CME association originated from an AR close to the disk (Figure 2f). During the end of Cycle 24, in years 2018 – 2019, there were no Type IV bursts observed at all.

Metric-Type II and deca-hectometer (DH)-Type II radio bursts are often used as an early indicator of CMEs and interplanetary CMEs (ICMEs). These DH-Type II bursts indicate the MHD shock entrance into the interplanetary medium. The CMEs associated with active regions close to the central meridian (the disk) are often responsible for geomagnetic storms, as those are in the Sun – Earth line of sight (see, e.g., Schwenn et al., 2005; Gopalswamy, 2010; Cid et al., 2014, and references therein). Since Type IV bursts are also associated with CMEs, these bursts can help understand the near-Sun development of interplanetary disturbances (Gary et al., 1985). Lately many authors have also used Type IV radio bursts as a means to extract near-Sun CME parameters. Gopalswamy et al. (2016) showed that moving Type IV bursts are associated with the moving flux ropes of the CMEs, therefore they can be used as a proxy to determine the electron density and magnetic fields of the CMEs in question (Gergely, 1986). Since the magnetic field is responsible for the CME eruption, evolution, and later its geoeffectiveness, moving Type IV bursts can aid in the determination of the latter (e.g. Bastian et al., 2001; Tun and Vourlidas, 2013; Carley et al., 2017). It has been previously reported by Gonzalez, Gonzalez, and Tsurutani (1990) and Echer, Gonzalez, and Tsurutani (2011) that the first peak in the two-peak variation of geomagnetic activities in previous solar cycles was due to CMEs. In this study, we found that moving Type IV bursts are almost exclusively associated with CMEs ($\approx 90\%$), they can be widely used for estimating the geoeffective CME magnetic fields. Kumari, Morosan, and Kilpua (2021) reported a high association of Type IV bursts with CMEs. This indicates that if a Type IV burst is present during a CME, it can be used for studying the electron-acceleration locations as well as the CME kinematics early during the eruption process. Salas-Matamoros and Klein (2020) studied stationary Type IV radio bursts and showed that they originate from the legs of the magnetic flux rope erupting into the high corona during the CME. This would imply that a CME eruption is necessary for the generation of stationary Type IV emission. A high association of stationary Type IV bursts with CMEs indicates that they can be used to estimate the magnetic field near the legs of the erupting flux ropes.

Figure 3 Histograms showing the variation of the active region location associated with different types of Type IV bursts in Solar Cycle 24. The first two rows correspond to all Type IV events, the middle two rows to moving Type IV bursts, and the last two rows to stationary Type IV bursts. The *cyan dashed* lines are Gaussian fits to the histograms.



Zhang et al. (2003) found that the most geoeffective CMEs originate from the western hemisphere. Geoeffective CMEs mainly originate within E20 (east) to W50 (west) longitude, i.e. close to the disk center (Zhang et al., 2003). We found that most of the Type IV bursts were associated with ARs close to disk center ($\approx 65\%$), hence they can be used to determine the physical parameters of at least some of the geoeffective CMEs near the Sun. With powerful radio instruments, like the upgraded Nançay Radioheliograph (NRH: Kerdraon and Delouis, 1997), the Low Frequency Array (LOFAR: van Haarlem et al., 2013), the Murchison Widefield Array (MWA: Tingay et al., 2013), and the Gauribidanur Radiograph (GRAPH: Ramesh et al., 1998), this type of study can further benefit in cases when the radio-source region of radio bursts can be identified using radio imaging.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Disclosure of Potential Conflicts of Interest There is no conflict of interest.

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